Abstract — One important step in zinc hydrometallurgy is the leaching process, which involves the dissolving of zinc-bearing material in dilute sulfuric acid to form a zinc sulfate solution. The key point in the control of the process is to determine the optimal pHs of the overflows of the continuous leach process and track them. This paper describes a model-based expert control system for the leaching process, which is being used in a nonferrous metals smeltery. Specifically, steady-state mathematical models and rule models are first constructed based on the chemical reactions involved, the empirical knowledge of engineers and operators, and empirical data of the process. Then, a methodology is proposed for determining and tracking the optimal pHs with an expert control strategy based on a combination of mathematical models and rule models of the process. The results of actual runs show that the proposed control strategy is an effective way to control the leaching process.

1. INTRODUCTION

THE MAIN PROCESSES IN ZINC HYDROMETALLURGY are leaching, purification and electrolysis (Mathewson, 1959; Zhuzhou Smeltry, 1973). Leaching involves dissolving zinc-bearing material in dilute sulfuric acid to form a zinc sulfate solution. Purification removes the impurities in this solution to make a satisfactory electrolyte. Finally, electrolysis is used to recover metallic zinc from the electrolyte as a high-purity product. The primary purpose of leaching is to dissolve as much of the soluble zinc in zinc-bearing material as possible. To achieve this, effective process control is imperative. Conventional control methods are based solely on mathematical models of the process. However, it is difficult to obtain the required performance by using these methods because of the complexity of the chemical reactions (Gui & Wu, 1995).

Recent advances in expert systems provide an effective way of controlling the leaching process. Since the 1980s, expert systems have been widely studied and applied to process control (Hayes-Roth, Waterman & Lenat, 1983; Jackson, 1986; Åström, Anton & Årzen, 1986; Liebowitz & DeSalvo, 1989; Efstatthiu, 1989; Gupta & Sinha, 1996). An expert system is a computer program that emulates the behavior of human experts within a specific well-defined domain of knowledge to solve a problem in the domain (Liebowitz, 1995). Such a system can be used to control a complex process possessing time-variation, nonlinearity and uncertainty factors if it is designed to perform control operations for the process (Cai, Wang and Cai, 1996). On the other hand, in the leaching process, complex relationships among the factors that cannot be expressed by mathematical models can be expressed by rule models. These rule models are based on the experience of experts and operators, and accumulated empirical knowledge of the process. Thus, the behavior of the process can be described by a combination of mathematical models and rule models. This makes it possible to control the process by expert control techniques.

The key problem in the control of the leaching process is to determine the optimal pHs of the overflows of the continuous leaches and to track them. Conventional control methods only track fixed pHs and make adjustments by adding dilute sulfuric acid to the process. The pHs are selected in advance. The amount of acid is determined solely on the basis of mathematical models obtained from the main chemical reaction equations. The mathematical models do not consider other chemical reactions, variations in the reaction conditions, or incompleteness of the reactions.
This paper describes a model-based expert control system for the leaching process (MECSL), which has been implemented in a nonferrous metals smeltery. MECSL solves the key problem in process control by using an expert control strategy based on a combination of steady-state mathematical models and rule models. Both types of models are based on the chemical reactions involved, the empirical knowledge of engineers and operators, and empirical data on the process. They fully considered the chemical nature and complexity of the process to maintain the optimal conditions for the chemical reactions. The results of some actual runs are presented at the end of this paper.

2. PROCESS DESCRIPTION AND SYSTEM ARCHITECTURE

The leaching process for which MECSL was designed uses neutral and acid continuous leach technology.

2.1. Process Description and Requirements

The leaching process is shown in Figure 1 (Zhuzhou Smeltery, 1973). The process consists of one series of neutral leaches and two identical series of acid leaches. The zinc-bearing material is delivered to a flotation cell and mixed with an oxidized iron solution and spent electrolyte. This solution is delivered to four classifiers. The overflow is pumped to the 1st tank of each acid leach series, and the underflow is milled by four ball mills and pumped to the 1st tank of each acid leach series. The spent electrolyte, which contains sulfuric acid, is also added to the neutral and acid leaches. The main reaction in the tanks is

$$\text{ZnO} + \text{H}_2\text{SO}_4 = \text{ZnSO}_4 + \text{H}_2\text{O}. \quad (1)$$

The solution is then sent to thickeners to settle. The overflow from the neutral leach is sent to the purification process in the form of a neutral zinc sulfate solution, and the underflow is added to the 1st tank of each acid leach series. The overflows from the acid leaches are pumped to the 1st tank of the neutral leach, and the residues are sent to the residue treatment process.

The concentrations of zinc and impurities in the neutral zinc sulfate solution from the neutral leach should satisfy the standards shown in Table 1. In addition, an important consideration in process control is to dissolve as much of the soluble zinc in the zinc-bearing material as possible. This requires optimal conditions for the chemical reactions. Generally, these conditions are influenced by many factors, such as the pH and temperature of the solution, the duration of the reaction, and the composition and particle size of the zinc-bearing material, etc. However, for steady-state operation, the main factor is the pHs of the overflows of the neutral and acid leaches. So, the key to process control is to determine the optimal pHs and to track them. Empirical knowledge and data on the process show that the pHs of the overflows have to be 4.8~5.2 for the neutral leach and 2.5~3.0 for the acid leaches to guarantee the optimal conditions.

2.2. Architecture of MECSL

MECSL uses the architecture shown in Figure 2 to satisfy the above requirements. The main components are an expert controller (EC), three 761 series signal-loop controllers, and an automatic measurement system (AMS). The EC is contained in an expert control computer system that is connected to the 761 controllers by using a special wiring concentrator and voltage converter, and to AMS by using a manufacturing automation protocol.

EC uses a reasoning strategy that combines forward chaining and model-based reasoning to determine the optimal pHs, and computes the target flow rates of the spent electrolyte added to the neutral and acid leaches, so as to achieve the optimal reaction conditions. The

<table>
<thead>
<tr>
<th>Metallic Elements</th>
<th>Standard Allowable Ranges (mg/l)</th>
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<tbody>
<tr>
<td>Zn</td>
<td>140000~170000</td>
</tr>
<tr>
<td>Cu</td>
<td>160~450</td>
</tr>
<tr>
<td>Cd</td>
<td>400~1000</td>
</tr>
<tr>
<td>Co</td>
<td>8~25</td>
</tr>
<tr>
<td>Ni</td>
<td>8~15</td>
</tr>
<tr>
<td>As</td>
<td>0.4~1</td>
</tr>
<tr>
<td>Sb</td>
<td>0.2~0.5</td>
</tr>
<tr>
<td>Ge</td>
<td>0.14~0.5</td>
</tr>
<tr>
<td>Fe</td>
<td>20~35</td>
</tr>
</tbody>
</table>
reasoning strategy is based on a combination of mathematical models and rule models of the process. The three 761 controllers track the target flow rates through PI control algorithms to ensure that the actual pHs match the optimal values. Three control loops are constructed for the neutral and acid leaches.

AMS consists of pH meters, temperature meters, automatic concentration analyzers, and flow meters, etc. It performs on-line measurement of the pHs, temperatures, concentrations and flow rates etc.

3. STEADY-STATE MATHEMATICAL MODELS AND RULE MODELS

Leaching can be considered to be a steady-state chemical process because it is generally run within a specific operating range. Hence, the behavior of the process can be described with a combination of steady-state mathematical models and rule models. The mathematical models are based on both the chemical reactions involved and empirical data on the process, and are modified in accordance with the empirical knowledge of engineers and operators and empirical data on the process. Production rule models of the If-Then form are used to represent the empirical knowledge on the process.

3.1. Steady-State Mathematical Models

The steady-state mathematical models are based on the following assumptions:

(1) The zinc-bearing material and the solution in the neutral and acid leach tanks are agitated and completely mixed;
(2) The temperature of the solution is uniform;
(3) The chemical reactions occur mainly in the leach tanks.

The mass balance principle (e.g. Inugita and Nakanishi, 1987) yields the following dynamic balance equation for the sulfuric acid in the neutral leach:

\[
\epsilon_N V_N \frac{dx_{Nh}}{dt} = F_{Co}(x_{Nh} - x_{Ch}) + F_{Ne}(x_{Nh} - x_{Ne}) + \sum_{i=1}^{2} F_{iAo} x_{Nh} - x_{iAh}) - \int_{0}^{V_N} r_{Nh} dV_N, \quad (2)
\]

where \(x_{Nh}\), \(x_{Ch}\) and \(x_{iAh}\) are the concentrations of sulfuric acid in the solution after the neutral leach, the classifiers and the \(i\)-th acid leach series, respectively; \(x_{Ne}\) is the concentration of sulfuric acid in the spent electrolyte added to the neutral leach; \(F_{Co}\) and \(F_{iAo}\) are the flow rates of the overflows from the classifiers and the \(i\)-th acid leach series, respectively; \(r_{Nh}\) is the flow rate of the spent electrolyte added to the neutral leach; \(V_N\) is the total volume of the neutral leach tanks; \(\epsilon_N\) is the ratio of liquid to solid in the solution in the neutral leach; and \(r_{Nh}\) is the reaction rate of sulfuric acid.

For steady-state operation, \(r_{Nh}\) is the steady-state reaction rate, so equation (2) becomes

\[
F_{Ne}(x_{Nh} - x_{Ne}) = r_{Nh} V_N - F_{Co}(x_{Nh} - x_{Ch}) - \sum_{i=1}^{2} F_{iAo} (x_{Nh} - x_{iAh}). \quad (3)
\]

Let \(f_{Ne}o\) denote the steady-state particle reaction rate of zinc oxide with sulfuric acid and \(x_{Co}\) denote the concentration of zinc oxide in the overflow from the classifiers. Then,

\[
\frac{M_{ZnO}}{M_{H_2SO_4}} r_{Nh} = F_{Co} x_{Co} f_{Ne}o \quad (4)
\]

is obtained for the zinc oxide in the neutral leach by the principle of steady-state mass balance, where \(M_{ZnO}\) and
$M_{H_2SO_4}$ are the molecular weights of zinc oxide and sulfuric acid, respectively. $x_{CZO}$ can be computed from
\[ x_{CZO} = \eta_{CZO} \mu_{CZO} \frac{1}{1 + k_{Co}}, \] (5)

where $\eta_{CZO}$ is the zinc oxide content of the zinc-bearing material; $\mu_{CZO}$ is the specific gravity of the zinc-bearing material; and $k_{Co}$ is the ratio of liquid to solid in the overflow from the classifiers.

Combining expressions (3), (4) and (5) yields
\[ F_{Ne} = \frac{1}{x_{Nh} - x_{Nhe}} \left[ K_{Nh} \frac{F_{Co}}{1 + k_{Co}} \hat{f}_{Nzo} \right] - F_{Co} (x_{Nh} - x_{Ch}) - \frac{2}{k_{Co}} \sum_{i=1}^{k_{Co}} F_{IaO}(x_{Nh} - x_{Ia}) , \] (6)

where
\[ K_{Nh} = \frac{M_{H_2SO_4}}{M_{ZnO}} \eta_{CZO} \mu_{CZO} V_{Nh} . \] (7)

$\hat{f}_{Nzo}$ can be estimated based on the experience of experts and operators and accumulated empirical knowledge on the neutral leach process. Using this estimate, $\hat{f}_{Nzo}$, in equation (6) yields
\[ F_{Ne} = \frac{1}{x_{Nh} - x_{Nhe}} \left[ K_{Nh} \frac{F_{Co}}{1 + k_{Co}} \hat{f}_{Nzo} \right] - F_{Co} (x_{Nh} - x_{Ch}) - \frac{2}{k_{Co}} \sum_{i=1}^{k_{Co}} F_{IaO}(x_{Nh} - x_{Ia}) . \] (8)

This is the steady-state mathematical model for determining the flow rate of the spent electrolyte added to the neutral leach.

The same method is used to obtain the flow rate of the spent electrolyte added to the acid leaches. Let $F_{Ia}$ denote the flow rate of the spent electrolyte added to the $i$-th acid leach series. Then,
\[ F_{Ia} = \frac{1}{x_{Ia} - x_{Iae}} \left[ K_{Ia} \frac{F_{Cu}}{1 + k_{Cu}} \hat{f}_{Iao} \right] - F_{Cu} (x_{Ia} - x_{Ch}) - \frac{2}{k_{Cu}} \sum_{i=1}^{k_{Cu}} F_{Nia}(x_{Ia} - x_{Nia}) , \] (9)

where
\[ K_{Ia} = \frac{M_{H_2SO_4}}{M_{ZnO}} \eta_{CZO} \mu_{CZO} V_{Ia} . \] (10)

$x_{Ia}$ is the concentration of sulfuric acid in the spent electrolyte added to the $i$-th acid leach series; $F_{Cu}$ and $F_{Nia}$ are the flow rates of the underflows from the classifiers and the neutral continuous leach that are added to the $i$-th acid leach series, respectively; $V_{Ia}$ is the total volume of the tanks in the $i$-th acid leach series; $\hat{f}_{Iao}$ is the estimated steady-state particle reaction rate for zinc oxide with sulfuric acid in the $i$-th acid leach series; and $k_{Cu}$ is the ratio of liquid to solid in the underflow from the neutral continuous leach.

Expressions (8) and (9) are taken as nominal steady-state mathematical models because they only concern the chemical reaction (1). However, there are also other chemical reactions and factors that influence the process. For these reasons, models (8) and (9) need to be modified by empirical knowledge and data on the process.

Let $x_{Nh}^g$ and $x_{Ia}^g$ denote the target concentrations of sulfuric acid in the solution after the neutral leach and the $i$-th acid leach series. From empirical knowledge, the target flow rates $F_{Nho}^g(k)$ and $F_{Iao}^g(k)$ of the spent electrolyte added to the neutral leach and the $i$-th acid leach series during the $k$-th period are given by
\[ F_{Nho}^g(k) = \alpha_N(k) F_{Ne}(k) + \sum_{i=0}^{k} \beta_N(l) \Delta x_{Nh}(k) , \] (11a)
\[ \Delta x_{Nh}(k) = x_{Nh}^g - x_{Nh}(k) , \] (11b)
\[ F_{Ne}(k) = \frac{1}{x_{Nh} - x_{Nhe}} \left[ K_{Nh}(k) \frac{F_{Co}(k)}{1 + k_{Co}(k)} \hat{f}_{Nzo}(k) \right] - F_{Co}(k)(x_{Nh} - x_{Ch}(k)) - \frac{2}{k_{Co}(k)} \sum_{i=1}^{k_{Co}(k)} F_{IaO}(k)(x_{Nh} - x_{Ia}(k)) ; \] (11c)
\[ F_{Iao}^g(k) = \alpha_A(k) F_{Ia}(k) + \sum_{i=0}^{k} \beta_A(l) \Delta x_{Ia}(k) , \] (12a)
\[ \Delta x_{Ia}(k) = x_{Ia}^g - x_{Ia}(k) , \] (12b)
\[ F_{Ia}(k) = \frac{1}{x_{Ia} - x_{Iae}(k)} \left[ K_{Ia}(k) \frac{F_{Cu}(k)}{1 + k_{Cu}(k)} \hat{f}_{Iao}(k) \right] - F_{Cu}(k)(x_{Ia} - x_{Ch}(k)) - \frac{2}{k_{Cu}(k)} \sum_{i=1}^{k_{Cu}(k)} F_{Nia}(k)(x_{Ia} - x_{Nia}(k)) , \] (12c)

where $\alpha_N(k)$, $\beta_N(l)$, $\alpha_A(k)$ and $\beta_A(l)$ are empirical coefficients determined from empirical knowledge.

Assume that $C_{Nopt}$ and $C_{Iopt}$ are the optimal pHs of the overflows from the neutral leach and the $i$-th acid leach series. The following expressions are used to obtain $x_{Nh}^g$ and $x_{Ia}^g$ from $C_{Nopt}$ and $C_{Iopt}$, respectively.
\[ x_{Nh}^g = \frac{M_{H_2SO_4}}{2M_H} 10^{(7 - C_{Nopt})} . \] (13)
\[ x_{Ia}^g = \frac{M_{H_2SO_4}}{2M_H} 10^{(7 - C_{Iopt})} . \] (14)

where $M_H$ is the atomity of hydrogen. Let $C_{Ch}$, $C_{Nh}$ and $C_{Ia}$ denote the pHs of the solutions from the classifiers and the neutral and acid leaches, respectively. Then, $x_{Ch}$, $x_{Nh}$ and $x_{Ia}$ can be computed from $C_{Ch}$, $C_{Nh}$ and $C_{Ia}$, respectively, by using expressions that have the same form as (13) and (14).
Expressions (11) and (12) are modified steady-state mathematical models of the leaching process that are used to determine the target flow rates of the spent electrolyte added to the neutral and acid leaches.

### 3.2. Rule Models

The optimal pHs are mainly related to the following factors:

1. The composition and particle size of the zinc-bearing material;
2. The temperature of the solution; and
3. The concentrations of zinc and impurities in the overflows from the neutral and acid leaches.

However, it is difficult to express the exact relationships among the optimal pHs and these factors by mathematical models alone. To obtain the optimal pHs and the corresponding target flow rates, empirical knowledge and data on the process are needed. They are represented by production rule models of the following form (Hayes-Roth, Waterman & Lenat, 1983; Jackson, 1986; Efstathiou, 1989; Ishiduka and Kobayashi, 1991)

\[ R^k : \text{If } \text{condition} \text{ Then } \text{action}, \]  

where \( R^k \) is the number of the rule model, \( \text{condition} \) is the operating state of the process or a logical combination, and \( \text{action} \) is the conclusion or operation.

How empirical knowledge and data on the process is obtained is an important aspect of the construction of rule models. Empirical knowledge is culled from engineers and operators. The following empirical methods were extracted from interviews with them:

1. Method of determining the optimal pHs from the composition and particle size of the zinc-bearing material, the temperature of the solution, and the concentrations of zinc and impurities in the overflows from the neutral and acid leaches.
2. Method of determining \( \alpha_N(k), \beta_N(k), \alpha_A(k), \beta_A(k), \hat{f}_{\text{N}0}(k) \) and \( \hat{f}_{\text{A}0}(k) \) from the composition and particle size of the zinc-bearing material, the temperature of the solution, and the concentrations of sulfuric acid in the overflows of the neutral and acid leaches and in the solutions added to the neutral and acid leach tanks.

The empirical data was culled from past operating runs, measured values and statistical data on the process. This kind of data contains statistical data on the relationships among the optimal pHs, the composition and particle size of the zinc-bearing material, the temperature of the solution, and the concentrations of zinc and impurities in the overflows from the neutral and acid leaches, etc. It is also a key to determining the optimal pHs and the appropriate target flow rates.

The main content of the condition part of form (15) is:

1. The composition and particle size of the zinc-bearing material (which are divided into \( m \) and \( n \) levels, respectively);
2. The temperature of the solution (high, medium, low, and not in the allowable range);
3. The concentrations of zinc and impurities in the overflow from the neutral leach (large, medium, small, and not in the allowable range);
4. The concentrations of sulfuric acid in the solutions added to the neutral and acid leaches (large, medium and small);
5. The pHs of the solutions from the classifiers, and from the neutral and acid leaches (large, medium, small, and not in the allowable range); and
6. The flow rates of the spent electrolyte added to the neutral and acid leaches (large, medium and small).

The main content of the action part is instructions to select the optimal pHs, and increase, reduce or maintain the target flow rates.

The optimal pHs are obtained from an expert decision table (EDT) and an expert turning mechanism (ETM) that show the relationships among the optimal pHs, the composition and particle size of the zinc-bearing material, the temperature of the solution, and the concentrations of zinc and impurities in the overflows from the neutral and acid leaches. EDT and ETM are constructed based on empirical knowledge and data on the process. Figure 3 shows a flow chart for determining the optimal pHs, where \( f_c \) and \( f_{ps} \) denote the levels of the composition and particle size of the zinc-bearing material; \( f_i \) denotes the level of the temperature of the solution; \( f_{\text{N}0z}, f_{\text{N}0c}, f_{\text{A}0z} \) and \( f_{\text{A}0c} \) denote the levels of the concentrations of zinc and impurities in the overflows from the neutral leach and the \( i \)-th acid leach series, respectively; and \( C_N \) and \( C_A \) are the initial values of \( C_{\text{N}0pt} \) and \( C_{\text{A}0pt} \), respectively. It is clear that the optimal pHs are determined in two steps:

1. \( C_N \) and \( C_A \) are obtained by EDT from \( f_c, f_{ps} \) and \( f_i \); and

![FIGURE 3. Flow chart for determining optimal pHs.](image-url)
(2) $C_{\text{Nopt}}$ is obtained by turning $C_N$ from $f_{\text{Ncz}}$ and $f_{\text{Nci}}$, and $C_{\text{Aopt}}$ is obtained by turning $C_{\text{IA}}$ from $f_{\text{Acz}}$ and $f_{\text{Aci}}$.

It is also assumed that a smaller $f_c$ and $f_{ps}$ correspond to a lower soluble zinc rate and a smaller particle size of the zinc-bearing material, respectively. EDT and ETM must be constructed so as to conform to basic rules (1) and (2), respectively:

1. $C_N$ and $C_{\text{IA}}$ increase as $f_c$ or $f_i$ decreases, or $f_{ps}$ increases;
2. $C_{\text{Nopt}}$ and $C_{\text{Aopt}}$ increase as $f_{\text{Ncz}}$ and $f_{\text{Acz}}$ decrease or $f_{\text{Nci}}$ and $f_{\text{Aci}}$ increase, respectively.

Based on the above basic rules and empirical knowledge and data on the process, rule models for determining the optimal pHs are constructed. For example, in the designed system, $m = 10$ and $n = 8$, and some rule models are as follows:

- $R^{N1}$: If $f_c = 1$ and $f_{ps} = 1$ and $f_i = \text{high}$
  Then $C_N = C_{N11h}$
- $R^{N2}$: If $f_c = 3$ and $f_{ps} = n$ and $f_i = \text{medium}$
  Then $C_N = C_{N3em}$
- $R^{N3}$: If $f_c = m$ and $f_{ps} = 2$ and $f_i = \text{low}$
  Then $C_N = C_{Nm2l}$
- $R^{N4}$: If $f_{\text{Ncz}} = \text{large}$
  Then $C_{\text{Nopt}} = C_N + \Delta C_{\text{NzI}}$
- $R^{N5}$: If $f_{\text{Nci}} = \text{small}$
  Then $C_{\text{Nopt}} = C_N + \Delta C_{\text{NZs}}$
- $R^{N6}$: If $f_{\text{Nci}} = \text{large}$
  Then $C_{\text{Nopt}} = C_N - \Delta C_{\text{NzI}}$
- $R^{A1}$: If $f_c = 1$ and $f_{ps} = 1$ and $f_i = \text{medium}$
  Then $C_{\text{IA}} = C_{\text{IA11m}}$
- $R^{A2}$: If $f_c = 4$ and $f_{ps} = 5$ and $f_i = \text{low}$
  Then $C_{\text{IA}} = C_{\text{IA45l}}$
- $R^{A3}$: If $f_c = m$ and $f_{ps} = n$ and $f_i = \text{high}$
  Then $C_{\text{IA}} = C_{\text{IAmnh}}$
- $R^{A4}$: If $f_{\text{Acz}} = \text{medium}$
  Then $C_{\text{Aopt}} = C_{\text{IA}} + \Delta C_{\text{IAzm}}$
- $R^{A5}$: If $f_{\text{Aci}} = \text{medium}$
  Then $C_{\text{Aopt}} = C_{\text{IA}} - \Delta C_{\text{IAim}}$
- $R^{A6}$: If $f_{\text{Aci}} = \text{small}$
  Then $C_{\text{Aopt}} = C_{\text{IA}} - \Delta C_{\text{Ais}}$

where $C_{N11h}$, $C_{N3em}$, $C_{Nm2l}$, $\Delta C_{\text{NzI}}$, $\Delta C_{\text{NZs}}$, $\Delta C_{\text{NzI}}$, $C_{\text{IA11m}}$, $C_{\text{IA45l}}$, $C_{\text{IAmnh}}$, $\Delta C_{\text{IAzm}}$, $\Delta C_{\text{IAim}}$, and $\Delta C_{\text{Ais}}$ are empirically determined positive values.

EC is designed to determine the optimal pHs and the target flow rates based on the mathematical and rule models.

4. EXPERT CONTROLLER STRUCTURE AND CONTROL ALGORITHMS

The structure of EC is shown in Figure 4. It consists of a preprocessing mechanism, database, knowledge base, inference engine and user interface.

The preprocessing mechanism filters and captures the characteristics of process data from AMS and the three control loops, i.e., it obtains all the content of the condition parts of form (15).

The preprocessed data are stored in the database, which also holds the quality requirements for the neutral zinc sulfate solution, measured and statistical data on the process, the reasoning results from the inference engine, etc.

The knowledge base stores the modified steady-state mathematical models, rule models, empirical data, calculation laws, etc.

The inference engine acquires data from the database, and then uses both the knowledge in the knowledge base and a reasoning strategy that combines forward chaining (Hayes-Roth, Waterman & Lenat, 1983; Jackson, 1986; Efstathiou, 1989) and model-based
reasoning (Inugita & Komayashi, 1991) to determine the optimal pHs and target flow rates. The target flow rates are sent to the 761 controllers.

The user interface is used to configure and edit the knowledge base, and to display and print data, graphs, reasoning results, etc.

From the view of control, EC can be considered to be an expert controller composed of two-degree-of-freedom (TDF) P and PI controllers with variable gains. The structure of EC is shown in Figure 5. The inputs of TDF-P are:

1. Quality requirements for the neutral zinc sulfate solution obtained from the neutral leach;
2. Feedforward data such as the composition and particle size of the zinc-bearing material, the temperature of the solution, and the concentrations of sulfuric acid in the solution added to the neutral and acid leaches; and
3. Feedback data such as the concentrations of zinc, sulfuric acid and impurities in the overflows of the neutral and acid leaches.

The inputs of TDF-PI are:

1. The optimal pHs, which are the reference inputs of the controller;
2. Feedforward data, which are mainly the concentrations of sulfuric acid in the solution and the flow rates of the solutions that is added to the neutral and acid leaches; and
3. Feedback data such as the pHs of the overflows of the neutral and acid leaches.

In fact, TDF-P and TDF-PI are nonlinear controllers. The outputs of TDF-P are the optimal pHs $C_{\text{Nopt}}$ and $C_{\text{iAopt}}$, the gains $\alpha_N(k)$, $\beta_N(k)$, $\alpha_A(k)$ and $\beta_A(k)$ of TDF-PI, and the steady-state particle reaction rates $\hat{f}_{\text{Naq}}(k)$ and $\hat{f}_{\text{iAzo}}(k)$. They are obtained by firing rule models such as $R_{\text{N}}^{\text{N}} \sim R_{\text{A}}^{\text{N}}$ and $R_{\text{A}}^{\text{A}} \sim R_{\text{A}}^{\text{N}}$, and may be different in every sampling period. Based on the optimal pHs and the gains, TDF-PI uses the steady-state mathematical models (11) and (12) to obtain the target flow rates of the spent electrolyte added to the neutral and acid leaches.

TDF-P is based on rule models and TDF-PI is based on steady-state mathematical models and rule models.

### 4.2. Algorithms for Determining Optimal pHs and Target Flow Rates

The expert control strategy for the leaching process has four steps:

1. Determine the optimal pHs $C_{\text{Nopt}}$ and $C_{\text{iAopt}}$;
2. Select the controller gains $\alpha_N(k)$, $\beta_N(k)$, $\alpha_A(k)$ and $\beta_A(k)$, and the steady-state particle reaction rates $\hat{f}_{\text{Naq}}(k)$ and $\hat{f}_{\text{iAzo}}(k)$;
3. Determine the target flow rates $F_{\text{Nq}}^*(k)$ and $F_{\text{iAe}}^*(k)$; and
4. Track $F_{\text{Nq}}^*(k)$ and $F_{\text{iAe}}^*(k)$.

EC performs steps (1) to (3), i.e., it determines the optimal pHs and the target flow rates through a combination of the modified mathematical models and rule models of the process and by using forward chaining and model-based reasoning.

Algorithms 1 and 2 below have been developed to determine the optimal pHs and target flow rates.

**Algorithm 1 (Determines pHs):**

1. Compute $f_{c}$, $f_{ps}$ and $f_{i}$ from the composition and particle size of the zinc-bearing material, and the temperature of the solution, respectively.
2. Determine $C_{\text{N}}$ and $C_{\text{iA}}$ by rule models such as $R_{\text{N}}^{\text{N}} \sim R_{\text{N}}^{\text{N}}$ and $R_{\text{A}}^{\text{A}} \sim R_{\text{A}}^{\text{A}}$, respectively.
3. Compute $f_{\text{NcZ}}$, $f_{\text{NcI}}$, $f_{\text{iA}}$ and $f_{\text{iA}}$ from the concentrations of zinc and impurities in the overflows from the neutral and acid leaches.
4. Determine $C_{\text{Nopt}}$ and $C_{\text{iAopt}}$ by rule models such as $R_{\text{N}}^{\text{N}} \sim R_{\text{N}}^{\text{N}}$ and $R_{\text{A}}^{\text{A}} \sim R_{\text{A}}^{\text{A}}$, respectively.

**Algorithm 2 (Determines target flow rates):**

1. Select $\alpha_N(k)$, $\beta_N(k)$, $\alpha_A(k)$, $\beta_A(k)$, $f_{\text{Naq}}(k)$ and $f_{\text{iAzo}}(k)$ based on $f_{c}$, $f_{ps}$ and $f_{i}$ as well as the concentrations of sulfuric acid in the overflows of the neutral and acid leaches and in the solution added to the neutral and acid leaches by using a method similar to that of algorithm 1.
2. Obtain $C_{\text{Ch}}$, $C_{\text{Nh}}$ and $C_{\text{iAh}}$, and also $k_{\text{Co}}(k)$ and $k_{\text{Ca}}(k)$, from AMS.
3. Compute $x_{\text{Nh}}$ and $x_{\text{iAh}}$ from $C_{\text{Nopt}}$ and $C_{\text{iAopt}}$ using expressions (13) and (14), respectively, and also $x_{\text{Ch}}(k)$ from $C_{\text{Ch}}$, $C_{\text{Nh}}$ and $C_{\text{iAh}}$, respectively, using expressions that have the same form.

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**FIGURE 5. Structure of EC from the control standpoint.**
as expressions (13) and (14).

(4) Determine the target flow rates $F_{\text{Ne}}^e(k)$ and $F_{\text{Ac}}^e(k)$ from mathematical models (11) and (12). If the values are outside the allowable range, they are set to an allowable value by firing suitable rule models.

Algorithm 1 and step (1) of algorithm 2 are curried out by TDF-P. Steps (2) to (4) of algorithm 2 are curried out by TDF-PI.

The target flow rates are tracked by the 761 controllers to ensure that the pHs of the overflows from the neutral and acid leaches match the optimal values.

5. SYSTEM IMPLEMENTATION AND RESULTS OF ACTUAL RUNS

The designed MECSL has been running in a nonferrous metals smeltery. It provides not only a desired product, but also significant economic benefits.

5.1. Implementation of ECFDSL

MECSL was implemented on an IPC 610 type computer system and three 761 series single-loop controllers, and run under the MS-DOS 6.22 operating system. The functions of EC are implemented in application software written in Borland C++ and 8086-series assembly language. The implementation of the functions of the three 761 controllers was achieved through their configuration.

AMS contains some special instruments that are used to measure different kinds of process data accurately. More specifically, flow rates are measured with E+H electromagnetic flow meters; pHs, with industrial pH meters; concentrations, with an X fluorescence analyzer; and weights, with electronic scales; etc.

5.2. Results of Actual Runs

Figures 6, 7 and 8 show some results of actual runs of MECSL. The dotted lines indicate the standard limits and the constraints given in Section 2.1. The optimal pHs of the overflows of the neutral and acid leaches were determined by EC and tracked by the 761 controllers. The optimal reaction conditions were maintained. It is clear that the pHs satisfy the given constraints, and that the concentrations of zinc and the major impurities in the neutral zinc sulfate solution meet the given standards. In addition, the concentrations of other impurities also meet the given standards.

Statistical data on the leaching process shows not only that the desired product is obtained, but also that the costs are considerably reduced. In particular, compared with the results for control based solely on the mathematical models of equation (1), the leach rate of zinc-bearing material is about 4.8% higher and the consumption of zinc-bearing materials is about 8.3% lower. This means that more metallic zinc can be recovered in a shorter production period.

6. CONCLUSIONS

This paper has described a model-based expert control system being used for the leaching process of a nonferrous metals smeltery. The results of actual runs of the control system show that an expert control strategy based on a combination of steady-state mathematical models and rule models is useful for the control of the leaching process. It has also been shown that the control system provides not only the desired product, but also significant economic benefits. In particular, the following conclusions can be drawn:

1. Steady-state mathematical models and rule models that express the complex relationships among the factors

![Graph of pH vs. time for neutral leach](image1)

![Graph of pH vs. time for first acid leach series](image2)

![Graph of pH vs. time for second acid leach series](image3)

![Graph of concentration vs. time for zinc](image4)
influencing the leaching process can be constructed based on the chemical reactions involved as well as on empirical knowledge and data on the process;

(2) The optimal pHs of the overflows of the continuous leach process and the target flow rates of the spent electrolyte added can be determined by combining steady-state mathematical models and rule models and by using forward chaining and model-based reasoning;

(3) The optimal chemical reaction conditions can be maintained by tracking the target flow rates that correspond to the optimal pHs. In addition, the tracking can be implemented by the conventional single-loop control technique.

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**REFERENCES**


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